

***XMM-Newton* view of MS0735+7421: the most energetic AGN outburst in a galaxy cluster**

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We discuss the possible cosmological effects of powerful AGN outbursts in galaxy clusters by starting from the results of an *XMM-Newton* observation of the supercavity cluster MS0735+7421.

1 Introduction

The majority of cooling flow clusters contain powerful radio sources associated with the central cD galaxies [1]. As indicated by high resolution X-ray images, these radio sources have a profound impact on the intra-cluster medium (ICM) – the radio lobes displace the X-ray emitting gas, creating X-ray deficient cavities ([10], [2], [6]). The recent discovery of giant cavities and associated large-scale shocks in three galaxy clusters (MS0735+7241 [11], Hercules A [12], Hydra A [13]) has shown that AGN outbursts can not only affect the central regions, but also have an impact on cluster-wide scales.

This new development may have significant consequences for several fundamental problems in astrophysics. The non-gravitational heating supplied by AGNs could represent an important contribution to the extra energy necessary to "pre-heat" galaxy clusters, thus explaining the steepening of the observed luminosity vs. temperature relation with respect to theoretical predictions that include gravity alone ([8], [15]). Powerful central AGN outbursts may also affect the general properties of the ICM (e.g., temperature and metallicity profiles, X-ray luminosity, gas mass fraction). It is essential to understand well the ICM physics and evaluate the potential impact of AGN outbursts on the mass vs. temperature (M - T) and luminosity vs. temperature (L - T) relations, which are the foundation to construct the cluster mass function and use galaxy clusters as cosmological probes.

We address these problems by studying the X-ray properties of the most energetic outburst known in a galaxy cluster. MS0735+7421 (hereafter MS0735) is at a redshift of 0.216. With $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 1 - \Omega_A = 0.3$, the angular scale is 3.5 kpc per arcsec.

2 *XMM-Newton* view of MS0735+7421

MS0735 was observed by *XMM-Newton* in April 2005 for a total clean exposure time of about 50 ksec. The X-ray image of the central region of the cluster (see Fig. 1, top) shows twin giant cavities having ~ 200 kpc diameter each, in agreement with results from the previous *Chandra* observation [11].

The presence of the radio source at the position coincident with the holes in the X-ray emission [11] implies that the cavities are filled with a population of relativistic electrons radiating at low radio frequencies. The cavities may also be filled with a shock-heated thermal gas that can contribute to the internal pressure necessary to sustain them. In order to investigate this hypothesis we performed a detailed spectral analysis by modeling the spectra extracted in the cavity regions (see Fig. 1, top) as the sum of ambient cluster emission and a hot thermal plasma, each with a characteristic temperature. Hints of a second thermal component with $kT > 10$ keV were found in the northern cavity, in agreement with similar estimates in other clusters ([2], [5], [9]).

We also attempted a study of the shock properties. *Chandra* observations reveal a feature in the X-ray surface brightness that has been interpreted as a weak cocoon shock driven by the expansion of the radio lobes that inflate the cavities [11]. Our results from a spectral analysis of the pre-shocked and post-shocked gas are consistent with *Chandra* ones, although *XMM-Newton*'s spatial resolution is too poor to unambiguously measure the temperature across the shock.

3 Do cavities affect the average cluster properties?

From the *XMM-Newton* observation of MS0735 we can get new insights to evaluate the impact of energetic AGN explosions on the general cluster properties and scaling relations, which are fundamental to use galaxy clusters as cosmological probes. The main results can be summarized as follows (see [7] for a more detailed discussion):

- The total energy in cavities and shock is $\sim 6 \times 10^{61}$ erg, making MS0735 the most energetic AGN outburst known so far. This energy is enough to quench the nominal $\sim 260 \text{ M}_{\odot} \text{ yr}^{-1}$ cooling flow and, since most of the energy is deposited outside the cooling region (~ 100 kpc), to heat the gas within 1 Mpc by $\sim 1/4$ keV per particle. It thus contributes a substantial fraction of the 1 to 3 keV per particle of excess energy required to preheat the cluster [15].
- The energetic outburst and the consequently rising cavities uplift the central cool, low-entropy gas up to large radii, and at the same time the compression in the shells increases the ICM density. This results in an

increase of emissivity and thus luminosity. An attempt to estimate the expected boost in luminosity is presented in Fig. 1 (bottom left), which shows a sketch of the simple phenomenological model of the structure and emissivity of the gas considered to evaluate the effect of the cavity expansion and compression of the ICM in the bright shells. We estimate that the luminosity is boosted by a factor which depends upon the cavity radius and shell thickness. For the particular configuration of the cavities observed in MS0735, we expect an increase in luminosity by a factor of the order of about 25% (see Fig. 1, bottom right), consistent with our measurements. The unabsorbed X-ray luminosity ([0.1-2.4] keV) estimated by the spectra extracted after excising the cooling flow region is $\sim 3.8 \times 10^{44}$ erg/s. To evaluate the effect of the cavities on the luminosity, this has to be compared with the value estimated by the spectra extracted after excising the cavity regions (the cavities lie outside the cooling region), which is $\sim 3.0 \times 10^{44}$ erg/s. In both estimates the missing luminosity expected from a β -model profile inside the masked regions is added back in. The increased emissivity due to the cavities could also lead to an overestimate of the gas mass fraction, in qualitative agreement with the high value ($f_{\text{gas},2500} = 0.165 \pm 0.040$) that we measure for MS0735.

- MS0735 is a factor ~ 2 more luminous than expected from its average temperature on the basis of the observed L - T relation for galaxy clusters ([8], see Fig. 2, left). This effect may be partially explained by the boost in luminosity due to the cavities. Besides this, no obvious immediate impact on properties such as the scaled temperature profile (see Fig. 2, right) and scaled metallicity profile show up from our analysis. Also, the quantities we measure for MS0735 are consistent with the M - T relation predicted by the cluster scaling laws. We conclude that violent outbursts such as the one in MS0735 do not cause gross instantaneous departures from cluster scaling relations (other than the L - T relation). However, if they are relatively common they may play a role in shaping these relations.

Acknowledgments

We thank A. Vikhlinin for sending the data used to make the plots in Fig. 2, right. This research is supported by NASA grant NNG05GK876 and by NASA Long Term Space Astrophysics Grant NA64-11025.

References

1. Burns, J. O. 1990, AJ, 99, 14
2. Blanton, E. L., Sarazin, C. L., & McNamara, B. R. 2003, ApJ, 585, 227
3. De Grandi, S., & Molendi, S. 2001, ApJ, 551, 153
4. Evrard, A. E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494

5. Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., & Perley, R. A. 2002, *MNRAS*, 331, 369
6. Gitti, M., Feretti, L., & Schindler, S. 2006, *A&A*, 448, 853
7. Gitti, M., McNamara, B. R., Nulsen, P. E. J., & Wise M. 2006, submitted to *ApJ*
8. Markevitch, M. 1998, *ApJ*, 504, 27
9. Mazzotta, P., Brunetti, G., Giacintucci, S., Venturi, T., & Bardelli, S. 2004, *Journal of Korean Astronomical Society*, 37, 381
10. McNamara, B. R., et al. 2000, *ApJL*, 534, L135
11. McNamara, B. R., Nulsen, P. E. J., Wise, M. W., Rafferty, D. A., Carilli, C., Sarazin, C. L., & Blanton, E. L. 2005, *Nature*, 433, 45
12. Nulsen, P. E. J., Hambrick, D. C., McNamara, B. R., Rafferty, D., Birzan, L., Wise, M. W., & David, L. P. 2005a, *ApJL*, 625, L9
13. Nulsen, P. E. J., McNamara, B. R., Wise, M. W., & David, L. P. 2005b, *ApJ*, 628, 629
14. Vikhlinin, A., Markevitch, M., Murray, S. S., Jones, C., Forman, W., & Van Speybroeck, L. 2005, *ApJ*, 628, 655
15. Wu, K. K. S., Fabian, A. C., & Nulsen, P. E. J. 2000, *MNRAS*, 318, 889

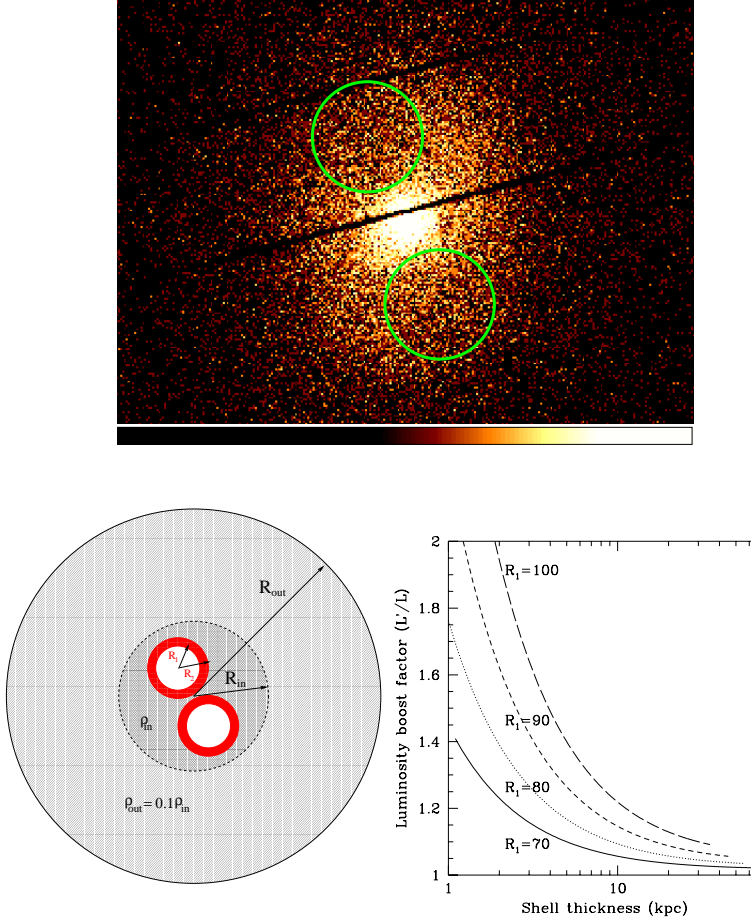


Fig. 1. (*Top*): MOS1 image of MS0735 in the [0.3-10] keV energy band. The image is corrected for vignetting and exposure. The circular regions considered for the spectral analysis of the cavities are indicated. The N and S cavities have a radius of ~ 100 kpc and are located at a distance of ~ 170 and ~ 180 kpc from the cluster center, respectively. (*Bottom, Left*): Geometry of the simplified phenomenological model considered in estimating the luminosity boost factor. During the cavity expansion, all the gas filling the cavities is assumed to be compressed into the bright shells. (*Bottom, Right*): Estimated luminosity boost factor due to cavity expansion and gas compression in the shells, as a function of the thickness of the shell (see left panel for the geometry considered). Different curves refer to different radius R_1 of the cavities (units in kpc). For an adiabatic index $\gamma = 5/3$, the maximum compression in a normal shock is a factor $f = 4$, so that the ratio of the shell thickness to the cavity radius is $R_2/R_1 - 1 > (1 + 1/f)^{1/3} - 1 \simeq 0.077$. For the cavities observed in MS0735 ($R_1 \sim 100$ kpc), the shell thickness is ~ 8 kpc, leading to a luminosity boost factor $\sim 25\%$.

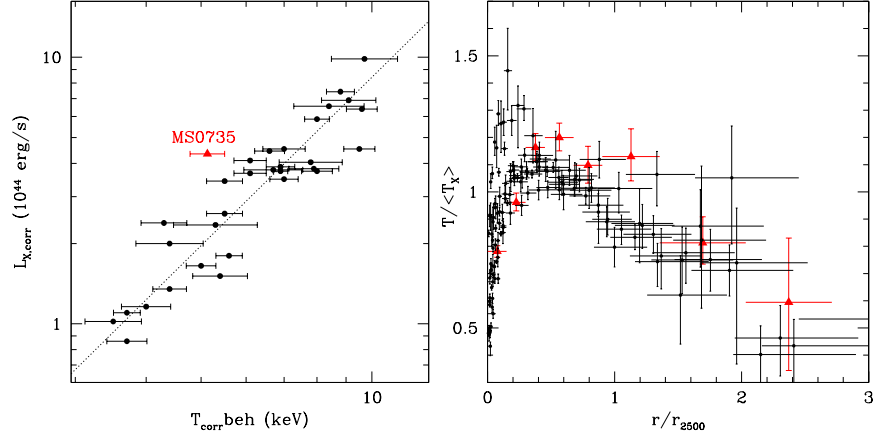


Fig. 2. (*Left*): Observed X-ray luminosities (corrected for the effect of cooling flows in the central 70 kpc) vs. emission-weighted temperatures (derived excluding cooling flow components) for a sample of nearby galaxy clusters [8]. The red triangle represents MS0735 data from the present observations. Note that, since the cooling flow region in MS0735 is bigger than the one adopted by [8] for the cluster sample, the effect of cooling flow is not completely corrected. (*Right*): Temperature profile measured for MS0735 (red triangles) overlaid onto the temperature profile observed for a sample of 12 relaxed clusters [14]. The profiles for all clusters are projected and scaled in radial units of r_{2500} . The temperatures are scaled to the cluster emission-weighted temperature excluding the central 70 kpc regions.